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TECHNICAL PAPER

Determination of tribological properties of aluminum cylinder by application of Taguchi method and ANN-based model

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Abstract

Energy losses due to friction and wear in reciprocating machines could be potentially reduced by applying new surface, materials and lubrication technologies for friction reduction and wear protection. In this paper, the tribological properties of ferrous-based reinforcements are tested and compared with aluminum alloy (EN AlSi10Mg) as a base material for cylinder of air compressor. The ball-on-plate CSM tribometer is used to carry out these tests under dry sliding conditions and constant sliding distance, for three different values of sliding speed and normal load. The wear factor is analyzed by using Taguchi method as well as artificial neural network-based model, with the aim of finding the optimal parameters. The result of signal-to-noise ratio and analysis of variance shows that the best tribological properties were achieved with reinforcements. Material has the greatest impact on the wear factor (35.54%), followed by load (22.16%) and sliding speed (6.01%). A good superposition was reached of the results obtained by the Taguchi method with the results of the artificial neural network-based model. According to the analysis of surface micrographs, it can close that the bonding material is the most dominant mechanism of wear for both tested materials.

Keywords Aluminum MMC cylinder · Wear factor · Taguchi method · ANN-based model

1 Introduction

City traffic and traffic flow have the greatest impact on the exhaust emission and air pollution, specifically in the street canyons, zones of city centers, etc. [1]. Moreover, in the area of city traffic it can give substantially a decline in exhaust emission, by application of various methods. Some of them are very effective and not too expensive, for instance:

- To switch on alternative fuels, natural gas and hydrogen as clean driving energy, with parallel introduction of flexible transport which enables to decrease the number of vehicles in urban centers to avoid congestion [1–7];
- Further optimization of vehicles and conventional internal combustion (IC) engines by lowering internal friction and mechanical losses, to lower fuel consumption and exhaust emissions [8–13].

With reciprocating machine optimization, by application of aluminum alloys for making of machine parts, we contribute to the lowering weight of engine and vehicle. Reduction in weight of the vehicle contributes to lower fuel consumption as well as exhaust emission.

However, aluminum alloys have specific disadvantages in the form of higher coefficient of thermal expansion and inadequate tribological (friction and wear) and mechanical (lower strength) characteristics.

Mechanical resistance of aluminum and improvement in the tribological characteristics were achieved by adding the right reinforcements during the formation of aluminum composite. Aluminum metal matrix composites (MMC) have a number of positive characteristics such as low density, good thermal conductivity and corrosion resistance [14].

As SiC, Al_2O_3 and graphite are commonly used as reinforcements, effect of SiC, Al_2O_3 and graphite on the tribological and mechanical characteristics is different. The

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increase in weight or volume fraction of SiC and Al_2O_3 contributes to better quality of mechanical characteristics, while from the second side, increasing the weight or volume of graphite improves tribological characteristics of the composite. By the combination of those two materials, we obtained the best value of the tribological and mechanical characteristics of the material [15–18].

Aluminum (MMC) which is reinforced with Mg_2Si particulates has shown improvement and advantages such as low density, excellent castability and excellent mechanical properties, especially under high temperature [18, 19]. Generally, Al–Mg_2Si (MMC) is chosen to replace Al–Si alloy in the manufacturing of automotive components such as piston, cylinder and brake disk [15, 19].

Some researchers have examined the possibility of improving the characteristics of friction and wear of sliding surfaces made of steel, by applying MoS_2 as a solid lubricant. Using laser technology, similar to the honing, on the surface of the metal, micro-reservoirs of certain density and layouts formed, into which the solid lubricant is then inserted [20, 21].

Similarly, as a solution to the problem, we investigated the application of several varieties of tribological inserts, made of cast iron and graphite as reinforcements for the cylinder liner and the piston skirt, inside reciprocating machines of aluminum as the base material [12, 15]. Previously, the surface of the cylinder of the base machine from gray cast iron was treated with honing, while the optimized aluminum construction was modified by adding a coating on the basis of iron using a spray method under atmospheric conditions (APS) [15, 18].

Based on the results of tribological tests [22, 23], using the Taguchi method and artificial neural network (ANN)-based model, we analyzed influence of control parameters, such as composition of the material, the load and the sliding speed, on the wear factor. For the purposes of adaptation and application of Taguchi method in this area, we used the available scientific papers, as the base literature.

Taguchi method is used to explore the weight loss of brake pads within the automotive braking systems [24], as well as for determination of production limits of friction materials [25]. In the field of tribology, the Taguchi method is used to explore the abrasive wear of pure titanium [26], as well as to optimize limits in the processing of MMC with aluminum base [27, 28].

The authors have also successfully used the Taguchi method in tribological optimization of hybrid composites with aluminum base [29–31]. In the field of mechanical construction and mechanization, the Taguchi method can be used, as example, for selecting the ideal toroidal pump and gear power transfer parameters [32, 33].

Validation of the results is carried out in parallel, using the ANN-based model. As a basis for modeling and calibration of the model, some of the available scientific results in this field are used [34–37].

In general, the goal is to make a right choice of the reciprocating machines construction (air compressor in our case), by using tribologically optimized construction of assembly (piston, piston rings and cylinder), based on the results of tribological research and modeling. We will do later on the test bench which designed for IC engines and compressors, the researches of service life, as well as performances of optimized experimental construction of reciprocating machine [9, 15, 22].

2 Modification of aluminum cylinder sliding surface

Mechanical efficiency of the IC engines and generally reciprocating machines is dependent on energy losses associated with friction, i.e., the conditions inside tribological system which consists of piston, piston rings and cylinder surface.

Because tribological properties of pure, non-machined and unprotected aluminum cylinder are bad, if compare with gray cast iron, as one of the solution to the problem is application of the cylinder liners made of cast iron, with parallel tribological measures for improving cylinder liners characteristics [8, 15]. However, the problems with cylinder liners of cast iron in applying technology are increased dimensions and weight of the machine [15, 38, 39].

Another solution is the protection of aluminum alloy by adding coatings as chemical and thermal treatments for cylinder sliding surface. Today, many makers successfully use thermal spraying as one of most predominant surface treatments, to make fully sprayed cylinder surface consisting of Fe–Al composite material with right tribological properties [18, 38, 39].

Friction losses inside the tribological system piston group and cylinder surface, from the second side, are directly related to the lubrication conditions between the piston ring and the cylinder. Therefore, lubrication and lubricants also have the effect on the wear intensity of piston rings and cylinder surface. The task of the lubricants is to make sure separate those surfaces in sliding contact, and to lower the friction and wear. Therefore, it is very important to apply proper lubricants in parallel with the new tribological materials for reciprocating machines [18, 39].

On the other hand, consumption of lubricating oil in piston machines is based on condition inside sliding parts of piston group. The aim is to correctly choose the parts of sliding contact, extend the service life of piston group parts and omit the piston machines. Undesirable presence of engine oil in the pressure pipe of the compressor in the air braking system of the motor vehicle is one of the reasons for researches in this field.

With the aim to achieving strength as well as tribological characteristics similarly as in the case of the application gray cast iron, we patented the cylinder of aluminum for reciprocating air compressor produced with the reinforcements consisting of mechanically stronger and tribological material. Internal surface of the aluminum cylinder as base material (alloy EN AlSi10Mg) is modified by putting reinforcements of cast iron that are arranged in the form of continuous pads, the plates or discrete tribological plugs in the form of spheres (nodule), or particles spherical shape. Construction of reinforced aluminum cylinder is described in more detail within the literature [12, 15, 22, 23].

3 Experimental setup

Tribological tests are carried out at CSM tribometer with ball-on-plate contact pair for different normal loads and sliding speeds in dry conditions [23].

Tribological tests are carried out based on variation of three different normal loads ($F_N = 0.3$, 0.6 and 0.9 N) and sliding speeds ($V = 3$, 9 and 15 mm s^{-1}). Duration of each test was 500 cycles (sliding distance of 1 m), and acquisition rate 100 Hz.

Testing is realized under low speed and loads. This is under the terms of the in-cylinder compressor in which the largest pressure is much lower than the pressure in the combustion chamber of the IC engines. Test conditions without lubrication are particularly interesting because they are increasingly exploring compressors without lubrication oil [40].

Continuous wear monitoring during linear reciprocating sliding is investigated. Penetration depth is a very sensitive parameter, and some caution should be applied when it is used as a parameter for the wear measurements. There are some interesting papers dealing with the problems of penetration depth [41, 42].

Penetration depth (PD) curves were obtained and analyzed. We continually monitor wear process by PD value, and we look at effects of changes in applied load and speed [23, 43].

3.1 Wear scar

Wear scar based on examinations of worn surfaces by optical microscopy is analyzed in comparison with trends of PD curves. Figures 1 and 2 present surface micrographs of base material and reinforcements after test under dry sliding, obtained for the same conditions of applied load and speed [23, 43]. It is noticeable that wear scar of aluminum alloy is higher than cast iron sample due to transfer material and consequent increase in coefficient of friction which occurs for aluminum.

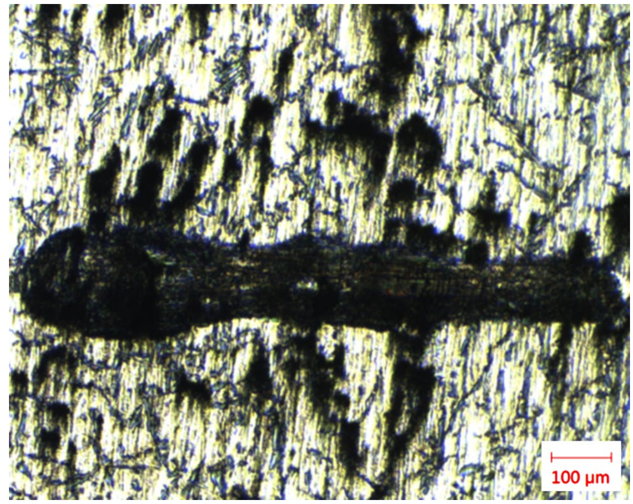

Fig. 1 Surface micrograph of base material after dry sliding test under ($F_N = 0.6$ N; $V = 15$ mm s^{-1})

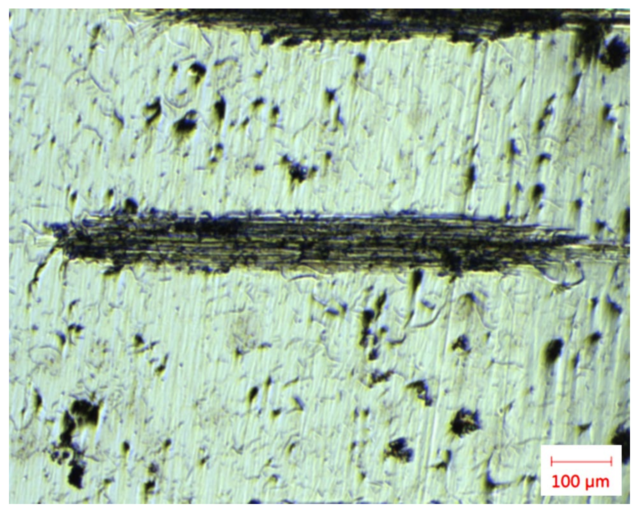

Fig. 2 Surface micrograph of reinforcement after dry sliding test under ($F_N = 0.6$ N; $V = 15$ mm s^{-1})

Deep grooves in analyzed surfaces indicate that the bonding material is the most dominant mechanism of wear for both tested materials. Similar conclusions can also be made when testing materials are at lower load and at the same sliding speed ($F_N = 0.3$ N; $V = 15$ mm s^{-1}) [23].

3.2 Design of experiments

Analysis of the wear of both the tested materials was performed on CSM tribometer, while control factors and their levels affecting the wear factor are given in Table 1. Wear tests were realized by changing three basic parameters

Table 1 Levels for various control factors

Control factors	Units	Level I	Level II	Level III
(A) Material	–	Base material	Reinforcement	
(B) Load	N	0.3	0.6	0.9
(C) Sliding speed	(mm/s)	3	9	15

(material, load and sliding speed). Wear factor is more clarified in the literature [41, 42].

The tests were conducted as per the orthogonal array with level of parameters given in each array row. The wear test results were subject to the analysis of variance (ANOVA) [28]. By application of Taguchi method, experimental results on CSM tribometer [23] are transformed in signal-to-noise (*S*/*N*) ratio.

S/*N* ratio, which condenses the multiple data points within a test, depends on the type of characteristics being evaluated. Characteristic in the form of *S*/*N* ratio "smaller the better" is used to analyze the wear factor inside the research work. The equation for calculating *S*/*N* ratio for Taguchi characteristic "smaller the better" is as follows:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right). \tag{1}$$

In the previous equation, n is the repetition number of each test and y_i is the result of the experiment for each test. We calculated *S*/*N* ratio for each level of influencing parameters by *S*/*N* analysis. Also, we used statistical analysis of variable to consider parameters statistically worth and we will predict ideal combination of parameters.

The calculated experimental results for wear factor are obtained by using orthogonal array for different factors' combinations, and they are given in Table 2. Table 2 lists the average values of *S*/*N* ratio or wear factor, as well as the results of ANN-based model. This is total wear factor (not steady state).

We used for the experimental design (to get different variances of response parameters) the orthogonal array L18 (Table 2) obtained by applying Taguchi mixed level design.

Wear factor is higher for reciprocating compressor base material. Only the value of wear factor under ($F_N = 0.3$ N; $V = 3$ mm s^{-1}) is higher for the reinforcement than for the base material, mainly due to the penetration of aluminum in cast iron. We can draw a similar conclusion at test condition ($F_N = 0.3$ N; $V = 9$ mm s^{-1}).

3.3 ANN-based model settings

Inspired by biological nervous system and in purpose of solving problems with the use of computers, we developed the proper ANN-based model. Application of ANN for problem solving is very wide, from business disciplines to scientific disciplines, and on this way saved the time and costs necessary for many of the experiments. The basic ANN consists of response layer, hidden layer and output layer [34–36].

Table 2 Experimental setup with L18 orthogonal array

	Material	Load (N)	Sliding speed (mm/s)	Wear factor (mm^3/Nm)	*S*/*N* ratio (dB)	ANN outputs
1	Base material	0.3	3	1.72E−5	95.2771	0.000149016
2			9	2.66E−5	91.4929	0.000037805
3			15	5.877E−4	64.6165	0.000576467
4		0.6	3	1.438E−4	76.8474	0.000142539
5			9	4.905E−4	66.1867	0.000489905
6			15	5.455E−4	65.2643	0.000534089
7		0.9	3	2.347E−4	72.5903	0.000236159
8			9	2.694E−4	71.3935	0.000276585
9			15	3.306E−4	69.6142	0.000333552
10	Reinforcement	0.3	3	3.57E−5	88.9579	0.000058368
11			9	2.88E−5	90.8077	0.000078315
12			15	2.55E−5	91.8627	0.000656695
13		0.6	3	6.88E−5	83.2493	0.000068265
14			9	5.19E−5	85.6899	0.000063868
15			15	4.98E−5	86.0516	0.000010194
16		0.9	3	8.54E−5	81.368	0.000096612
17			9	6.58E−5	83.6412	0.000077684
18			15	4.57E−5	86.7951	0.000070683

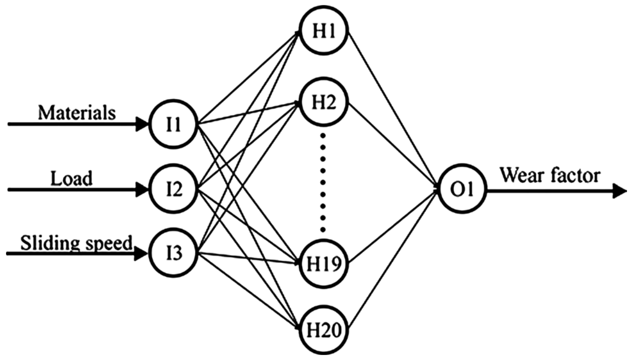

Fig. 3 Network structure

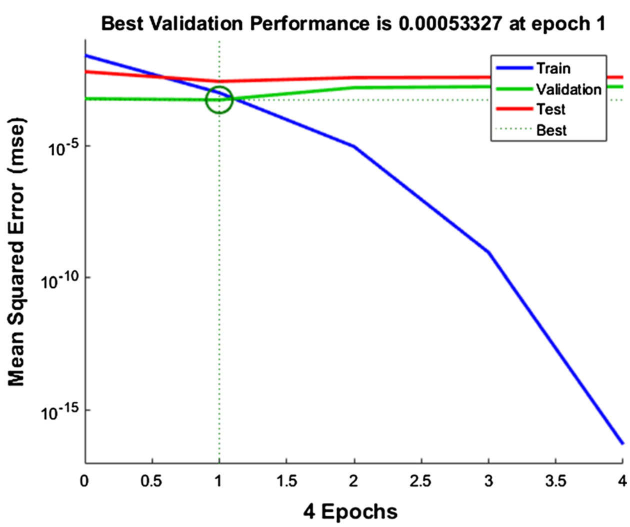

Fig. 4 Mean square error plot for the trained neural network

For prediction of wear factor, in this paper, we used neural network with one hidden layer and 20 neurons in this layer, and scheme of this network is shown in Fig. 3.

Software used for training of neural networks is commercial MATLAB 2016a. Activation function that is used for training of ANN is logarithmic sigmoid transfer function or short (logsig), and algorithm that is used for training of network is the Levenberg–Marquardt algorithm. All data are divided into three groups: training, test and validation data, which use 70%, 15% and 15% of all data obtained by experiment, respectively. Figure 4 shows the mean square error (MSE) plot for the trained neural network, and one can notice from this plot that there is no problem in the training of the network since the validation and test curves are similar. After the training of the neural network also, the regression plot is obtained for training, validation, test samples and overall (*R*) values for all samples that is 0.99561 (Fig. 5).

4 Results

4.1 Analyses of *S*/*N* ratio

The influence of control limits, such as material, load and sliding speed on wear factor, was confirmed by the analysis of *S*/*N* ratio. The Minitab 16 statistical commercial software is used to form an orthogonal matrix. Arithmetic mean of the *S*/*N* ratio is calculated for each level of considered factors in comparison with wear factor. Process value settings with the highest *S*/*N* ratio always yield the best quality with minimum variance.

The response table gives the influencing order of the limits on wear factor under dry sliding conditions (Table 3). We determinate the control value with strongest influence by differences between the greatest and least mean value of the *S*/*N* ratio. The higher the difference between the mean of *S*/*N* ratios, the more influential will be the control value.

The high influencing value is determined through its delta value. The difference between the maximum and minimum value of the *S*/*N* ratio gives the delta value. The value with the highest delta value denotes that it has major influence on the wear factor. The effects of the control parameters on the wear factor are listed in Table 3. Based on the ranking may be noted that the material has more impact on wear factor followed by load and sliding speed.

Figure 6 shows a graph of the main effects of the influence of the various testing limits on the wear factor. In the main effect plot, if the line for a particular value is near horizontal, then the value has no significant effect. In contrast, a value for which the line has the highest inclination has the most significant effect. In the given case, the greatest influence on the wear factor is the tested material and sliding speed, for constant sliding distance. The impact of the load on the wear factor is much smaller.

4.2 Analysis of variance results for wear test

Experimental results are analyzed by using ANOVA software used for studying the influence of the considered parameters, materials, loads and sliding speed on the wear factor. By performing the analysis of variance, one can decide which independent factor dominates over the other and the percentage contribution of that particular independent variable [28].

Table 4 presents the ANOVA results for wear factor for three factors, variation and interactions of those factors. This analysis is performed for a significance level of 5% ($\alpha = 0.05$), i.e., for a confidence level of 95%. Sources with a *P* value less than 0.05 were considered to have a

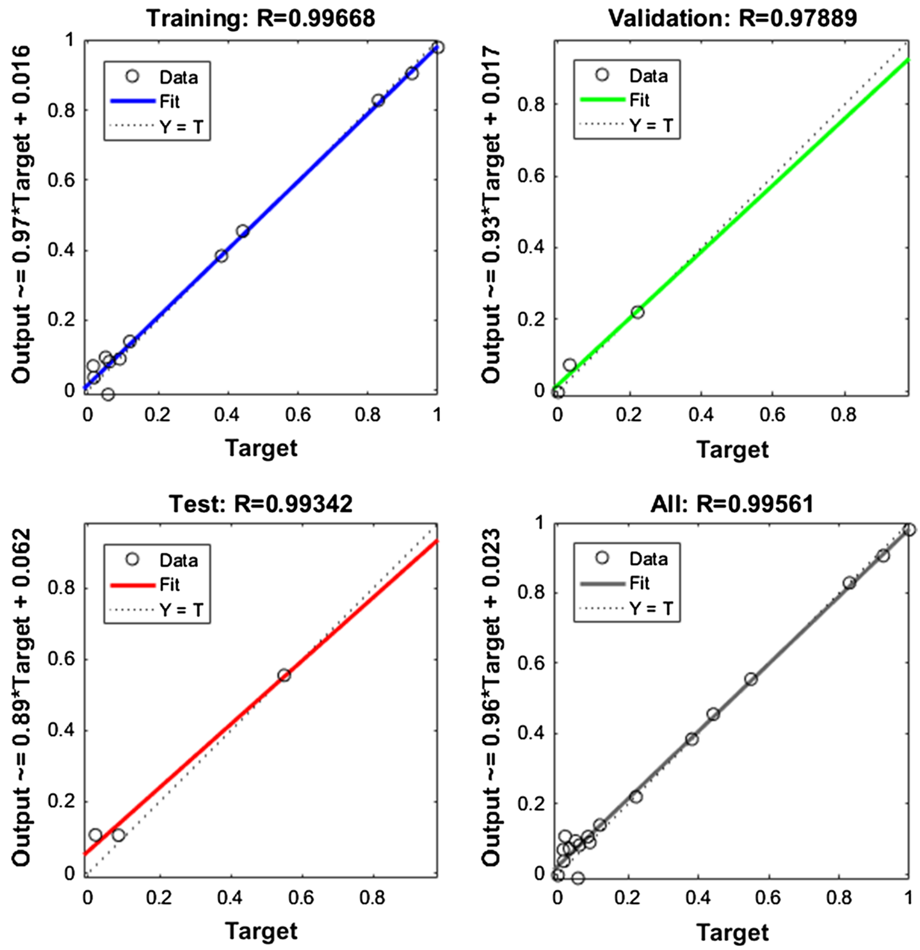

Fig. 5 Predictive performance of ANN-based model

Table 3 Response table for *S/N* ratios; case smaller is better (wear factor)

Level	Materials	Load	Sliding speed
1	74.81	87.17	83.05
2	86.49	77.21	81.54
3		77.57	77.37
Delta	11.68	9.95	5.68
Rank	1	2	3

statistically significant contribution to the performance measures. In Table 4, the last column shows the percentage contribution (Pr) of each value on the total variation indicating its degree of influence on the result.

Table 4 shows that the material has the greatest impact on the wear factor (35.54%).The load has less impact on the wear factor (22.16%), while sliding speed has the least significant impact (6.01%).

Interactions between other individual parameters have significant impact, too. For example, the influence of interaction of material and sliding speed is the greatest (15.55%), followed by interaction of load and sliding speed (9.37%) and interaction of material and load (3.52%).

Figure 7 shows the interactions of each parameter with the wear factor.

Based on the obtained parameters (Table 4), in Figs. 8 and 9, 2D and 3D diagrams are shown which are the dependence of the wear factor from load as well as the sliding speed.

According to the performed analysis and given graphs, minimal wear factor is achieved with low load under lower sliding speed conditions. Also, wear factor increases with increasing load and sliding speed.

Comparison of the linear regression line obtained on the base of experimental results of the wear factor with the predicted values is shown in Fig. 10. The linear regression equation is obtained by application of ANOVA with materials, normal load and sliding speed as variables, too [29].

A graphic comparison of experimental results achieved by the Taguchi method and ANN-based model is shown in Fig. 11. One can obtain a good superposition of results by Taguchi method and ANN-based model.

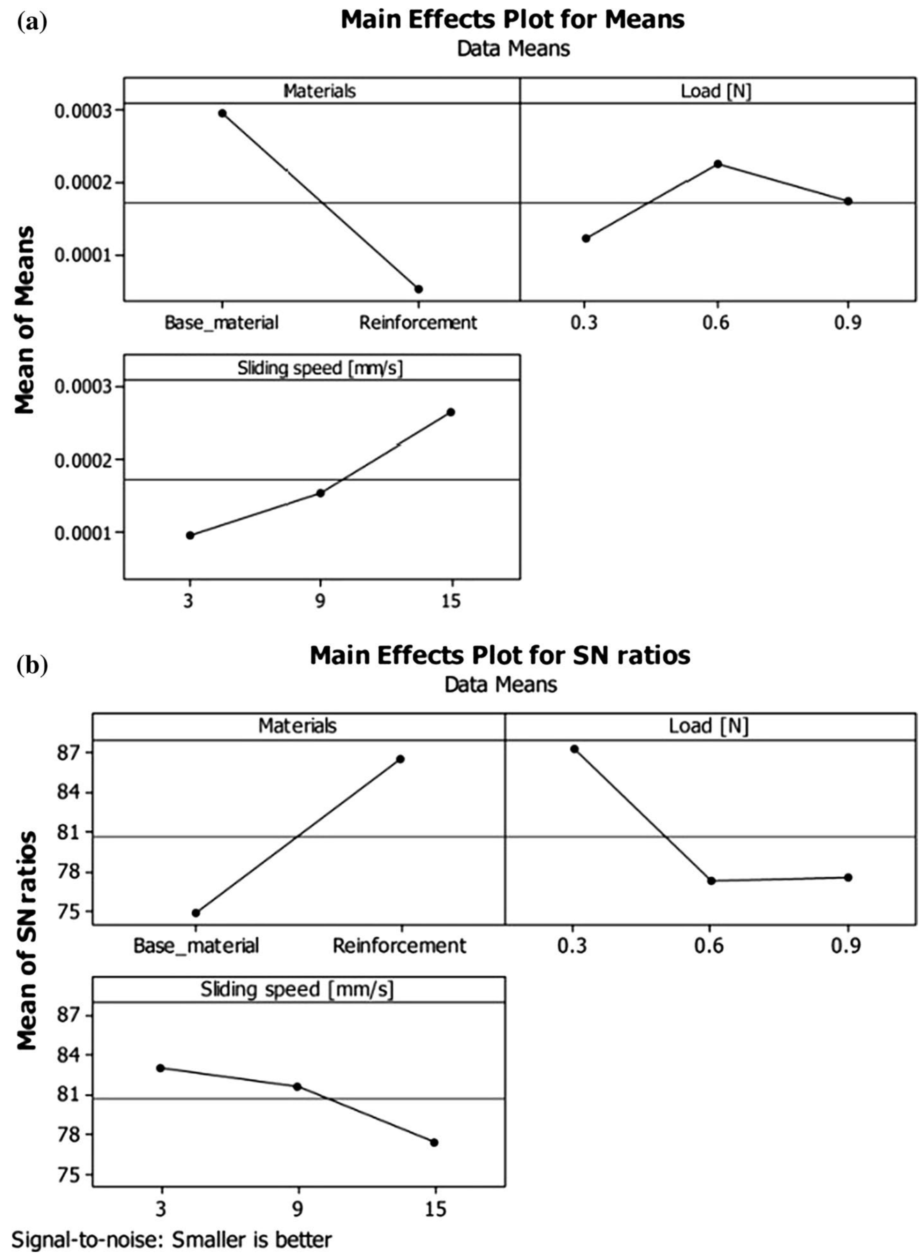

Fig. 6 Main effect plot for: **a** means—wear factor and **b** *S*/*N* ratio—wear factor

Table 4 Analysis of variance for wear factor

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Pr (%)
Materials	1	614.14	614.14	614.14	18.11	0.013	35.54
Load	2	382.82	382.82	191.41	5.64	0.068	22.16
Sliding speed	2	103.87	103.87	51.93	1.53	0.321	6.01
Materials vs load	2	60.80	60.80	30.40	0.90	0.477	3.52
Materials vs sliding speed	2	268.61	268.61	134.31	3.96	0.113	15.55
Load vs sliding speed	4	161.95	161.95	40.49	1.19	0.434	9.37
Residual error	4	135.68	135.68	33.92			
Total	17	1727.87					100.00

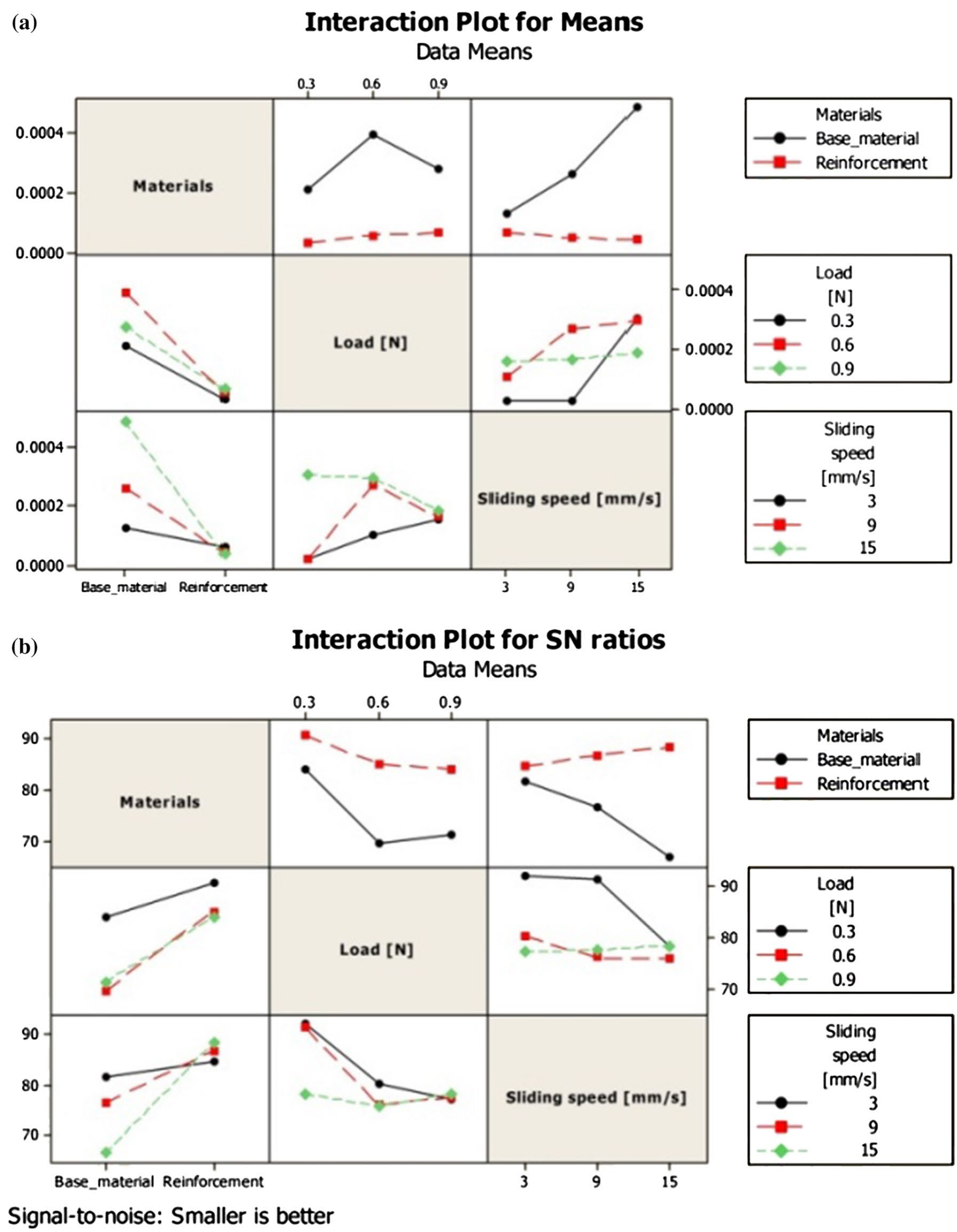

Fig. 7 Interaction plot for: **a** means—wear factor and **b** *S/N* ratio—wear factor

5 Conclusion

Taguchi design method and ANN-based model are applied to analyze the wear factor problem of the materials for air compressor cylinder under dry sliding conditions as described in the manuscript. From the study performed during experimental work and presented modeling, the following generalized conclusions were formulated:

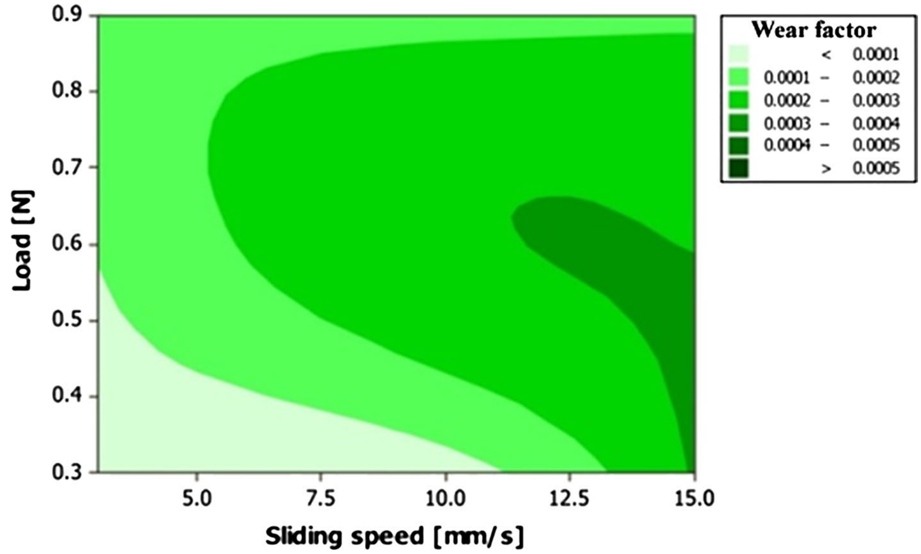

Fig. 8 Contour plot for dependence between wear factor of the load and sliding speed

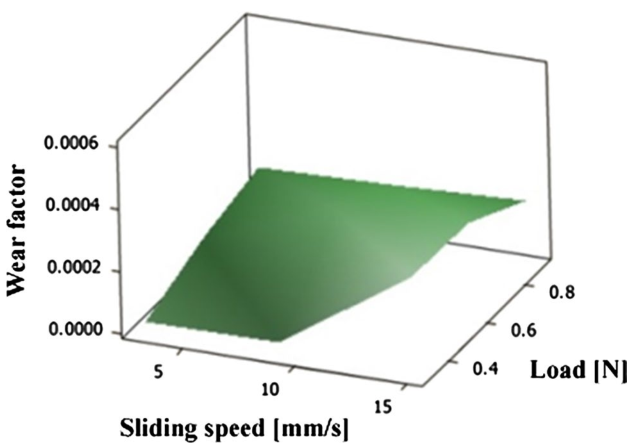

Fig. 9 Surface plot for showing dependence between wear factor of the load and sliding speed

- By application of aluminum alloys for making of machine parts, we contribute to the lowering weight of engine and vehicle. Reduction in weight of the vehicle contributes to lower fuel consumption as well as exhaust emission;
- The problems of lower strength as well as the poor tribological characteristics of the cylinder which are made of aluminum alloy for application in reciprocating air compressor for brake system of heavy-duty vehicles have been solved by application as base material with reinforcements of mechanically stronger and tribological material;
- Taguchi design method is suitable to analyze the wear sliding behavior problem as described in this manuscript. It is found that the value design of this method provides a simple, systematic and an efficient method for optimization of the wear test limits;

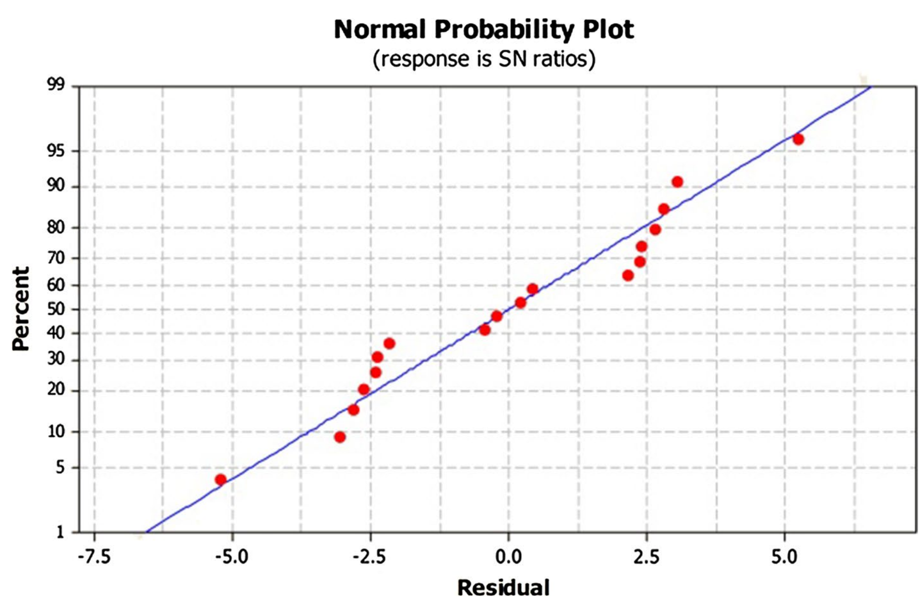

Fig. 10 Comparison of the linear regression model with experimental results for the wear factor

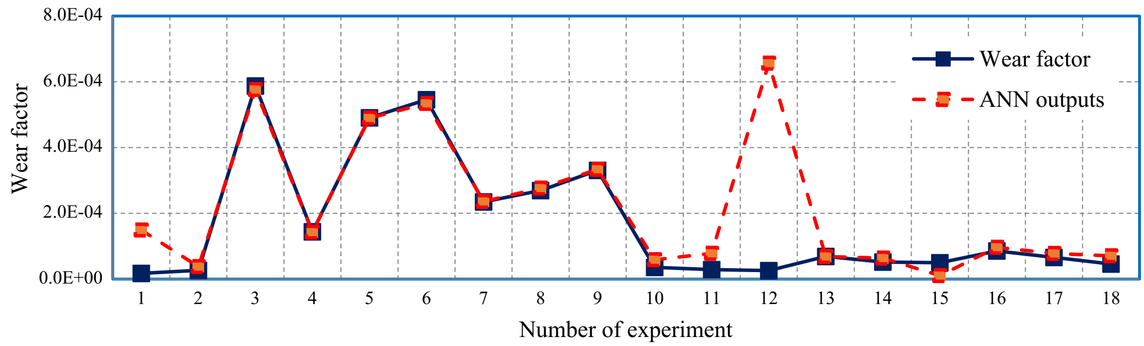

Fig. 11 Comparison of experimental results with the results of ANN-based model

- The material has the greatest impact on the wear factor (35.54%). The load has less impact on the wear factor (22.16%), while sliding speed has the least significant impact (6.01%). Interactions between other parameters have significant impact, too. Influence of interaction of material and sliding speed is the greatest (15.55%), followed by interaction of load and sliding speed (9.37%) and interaction of material and load which is 3.52%;
- The estimated *S*/*N* ratio using the ideal testing limits for wear factor could be calculated, and a good agreement between the predicted and real wear factors value is observed for a confidence level of 99.5%; and
- During experimental researches and modeling, it is achieved good superposition of results by Taguchi method and ANN-based model.

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